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"GUIDANCE TRADES FOR INTERCEPTORS NOT CONSTRAINED BY GROUND-BASED RADAR"

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ABSTRACT

Virtually all U.S. ballistic missile interceptor designs under development utilize terminal seekers that are cued by high-resolution, surface-based radars. The radar is used for target tracking leading to a fire-control solution, for midcourse target state updates and for end-game target discrimination. New space-based sensor systems such as SBIRS-low are seen as an adjunct that can be used to achieve range extension by cueing of radars and in some concepts, kinematic range extension of interceptors by providing for earlier launch commitments. The availability of global track information from space-based systems, however, coupled with the large design space provided by high throw-weight, retooled SLBM launchers enables an entirely new design concept for national missile defense. The notional system would utilize existing infrastructure, minimally modified SLBM launchers, and exoatmospheric kill vehicles currently under development for global coverage from a few sea-based locations against modest-intensity NMD threats. The post-boost "bus" would dispense multiple kill vehicles and would provide a platform to mount communication, sensors, and possibly special "fly-ahead" packages for mechanizing novel approaches to target discrimination. Assuming that ABM treaty barriers were successfully negotiated, the global coverage of this outermost tier to a layered NMD could simultaneously provide a stabilizing extension of NMD to regional allies.

NMD Challenges and Opportunities

National Missile Defense (NMD) challenges include technical and policy based components. The latter derives from the interaction of proposed NMD constructs with ABM and START treaty constraints, with perceptions of the urgency of the threat and of the likelihood of technical success, and with the cost and time to implement NMD. The technical challenges go to the extremely high cost of leakage and the requirement for nearly perfect coverage including all states at all times, the wide range of threat systems and potential launch locations, and the cost- exchange for threat evolution versus defense upgrades.

These were some of the same issues that attended the debate about the proposed Strategic Defense Initiative (SDI). The mitigating factor in the current NMD challenge is that the former SDI threat of thousands of warheads from the former Soviet Union has evolved to a requirement to counter a limited number of accidental launches, unauthorized launches or rogue state launches. Relative to the SDI requirement, the NMD threat is substantially reduced in size, complexity and technical sophistication. Although NMD population

defense is still a daunting problem, the challenge is now technically feasible subject to caveats about the cost to deploy such a defense.

At the same time, the START launcher reductions provide an opportunity to consider the reuse of amortized SLBM infrastructure and launchers to contribute an outermost tier to NMD. Although sea-based missile defense and space-based sensors for fire-control are proscribed by the current ABM treaty, the treaty as it stands would also preclude an effective 50-state NMD by the conventional approach using high-resolution surface-based radars. Assuming that treaty renegotiations would encompass elements of the concept proposed here, including sea-basing, fire-control using SBIRS-low, and staging multiple interceptor kill vehicles from a common booster, it is also necessary to consider constraints that would be imposed by the START treaties.

Those SLBMs that were adapted for NMD would have to be counted against total offensive launcher limits imposed by START. It is possible to envision entire submarines with SLBMs devoted to NMD as well as patrols with mixed loads of offensive SLBMs and NMD SLBMs. For the latter case, verification concerns may cause the entire boatload of SLBMs to be counted against START limits.

The remainder of this paper will explore system issues relating to the viability of the proposed concept. This will include the application of models for threats, tracking sensors, composite filters using Early Warning Radars (EWRs) and space-based sensor information, and interceptors in a simulation-based analysis. Topics addressed will include the concept of operation for the notional system, tracking, kinematics,

terminal seeker acquisition, discrimination, divert and lethality.

Notional Concept of Operation

The concept of operation is illustrated in Figure 1, the timeline for key events. Central to the concept is the deployment of the Space Based Infrared System (SBIRS) - low, a constellation of a couple of dozen low
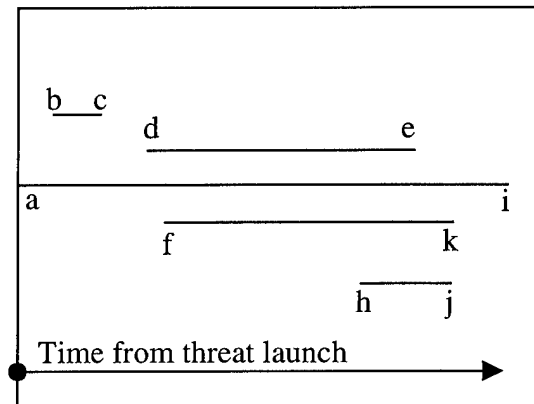

Figure 1. Timeline for Sea-Based NMD

Earth orbit satellites with infrared sensors to track warm and cold missile bodies and reentry vehicles from the end of boost until reentry.

The letter codes are as follows:
a = threat booster launch at time = 0
b = first observation by DSP or SBIRS-high at cloudbreak (e.g. 50 seconds)
c = last observation by DSP or SBIRS-high at booster burnout (e.g. 240 seconds)
d = first observation by SBIRS-low
e = last observation by SBIRS-low
f = interceptor booster launch
h = optional acquisition by terminal surface radar
j = last observation by terminal radar
k = interceptor impact
i = threat vehicle or debris impact (e.g. 2000 seconds from launch)

For successful interception, there are additional events that are not specifically

annotated, including possible guidance corrections using midcourse target state updates, threat cloud acquisition by the interceptor terminal seeker, discrimination and kill assessment.

The salient points about this concept that are illustrated by the graphic are

- the interceptor is launched toward a predicted intercept location based on SBIRS-low track information
- this event occurs early in the threat trajectory leading to a long flyout time for the interceptor and a potentially huge kinematic footprint.
- discrimination must be autonomous to the interceptor

The use of the retooled SLBM booster is also a key element in providing the huge kinematic footprint, the throw weight to mount packages for discrimination and the staging of multiple kill vehicles for sequential attack on multiple targets in the vicinity. The divert capability provided by the post-boost bus (possibly with higher thrust engines) and the ability to fit a kick stage in back of each kill vehicle in the throw weight budget are also important for launch commitments using lower accuracy initial track data. The design space provided by the throw weight margin enables engineering trades to be made to increase the likelihood of terminal seeker acquisition after long flyouts, including the use of bus-mounted sensors and the possible use of a search phase during acquisition. An LWIR seeker (6-11 microns) on the bus would have sufficient acquisition range to vector kill vehicles.

Effect of Tracking Errors on Fire Control

The full range of missile tracking sensors was examined for use in the notional concept. This includes DSP or the SBIRS-high replacement, SBIRS-low, the network of Early Warning Radars (possibly upgraded), and terminal area surface-based

radars such as Aegis and theater and NMD ground-based X-band radars.

A composite tracking filter was employed using multiple DSP or SBIRS-high sensors for boost-phase tracking and a separate composite filter was employed for ballistic tracking by all of the remaining sensors together including both radar and space-based infrared sensors. The sensors were modeled by a location, angular sector coverage, maximum range, sampling rate and revisit time, and by sensor random noise errors. The latter included azimuth, elevation, range and range rate for radars and only the first two measurements for infrared sensors. The ground rules for the boost-phase filter were that there should be no credit taken for and no variation in filter performance as a function of detailed knowledge of the threat characteristics. Fully coupled extended Kalman filters were mechanized for both 9-state and 12-state target models, with neither model employing a model for booster acceleration profile.

The results of the boost phase analysis of intercept point prediction errors indicated that the geosynchronous infrared sensors do not appear to provide accurate enough information to assure success of the acquisition phase and a reasonable divert budget for the long flyouts that would be enabled. The current DSP suffers from a low sample rate and inaccurate estimation of booster cutoff time. The 12 state filter improved estimation with respect to the 9 state filter but not enough to overcome the shortcomings. The results for prediction errors using unclassified, estimated parameters for the infrared sensors in geostationary orbit are given below in Table 1. The results are reported for 100 run Monte Carlo where the threat booster launch and impact sites were sampled to generate a range of viewing geometries. The key errors

are the velocity estimation errors at burnout, since these increase the position estimation errors linearly on ballistic propagation forward to intercept times. The velocity error out of the inertial ballistic flight plane is quite small, but the in-plane errors result in excessively large handover uncertainty for terminal systems on the interceptor.

Error Component	Stereo Geo IR Sensor	Stereo Geo with Burnout Sensor
Position (km)	6.5	6.5
In Plane Velocity (m/s)	310	280
Out of Plane Velocity (m/s)	20	19
In plane Uncertainty at 1600 sec (km)	493	480
Out of Plane Uncertainty at 1600 sec (km)	21	21

Table 1 - Estimation and prediction errors using geostationary infrared sensors

The improvement with higher data rates in SBIRS-high and the addition of a booster burn-out sensor did not substantially change the conclusion regarding applicability for fire-control decisions assuming that no credit is taken for knowledge of booster acceleration truth models.

Unclassified information on the network of present and upgraded Early Warning Radars was also considered for use in the fire control of the notional concept. The great advantage of these sensors is that they exist and can contribute to the composite track solution. The drawback is that there are some NMD threat trajectories that do not fall within the range and angular coverage of these sensors. For cases with coverage, the time when a line of sight is established is significantly later than for the SBIRS solution and precludes the great kinematic footprint advantage that the latter gives to the notional concept.

Absent any definitive parameters for SBIRS, some unclassified guesses at constellation and sensor parameters were used to run a simulation and composite tracking filter. Using a constellation of 24 GPS-like orbital parameters but with the altitude backed down to 1600 km, there appeared to be adequate composite tracking opportunities after threat boosters ascended to 1000 km and became visible above the Earth limb to SBIRS sensors. Depending on assumptions about revisit rate and sensor resolution, the range of 1-sigma velocity uncertainty seems to be about 10-20 meters/second at worst. Extrapolating 500-1500 seconds into the future for typical intercept times, this translates into a doable acquisition and divert endgame requirement and is a key enabler of the proposed concept.

Terminal Sensor Acquisition

Most NMD concepts employ a lightweight terminal seeker with a body-fixed infrared sensor array. To provide enough range to achieve a divert with limited acceleration, the sensor is desired to have high sensitivity and at the same time the ability to resolve and discriminate reentry bodies from debris or other objects and to select an aimpoint on non-separated warheads. To simultaneously achieve high resolution and good sensitivity, the sensor design is driven to a very narrow field of view concept wherein the sensor

must be oriented on first operation so that the target appears in its field of view. At NMD closing velocities that may range up to 10-12 km/sec, the time required to divert with limited acceleration does not allow the luxury of a search phase for initial acquisition. Target prediction errors or other system issues that place the target outside of the sensor field of view will result in failure to acquire and failure to guide to an intercept.

The proposed concept would provide the ability to mount a more substantial stabilized sensor on the post-boost bus that could provide a longer-range acquisition and could support the higher reliability of a search phase. The bus-mounted sensor could support the operation of multiple kinetic kill vehicles, each with their own, more limited but autonomous terminal seeker. Information from the more capable bus-mounted sensor would enhance the probability of successful acquisition by the seekers on the kill vehicles, an important consideration given that the target track and target prediction errors are more substantial than for concepts that employ a high-resolution ground-based radar. The bus-mounted sensor might also be used to provide some degree of kill assessment.

Alternative Discrimination Techniques

Traditional countermeasures that might be dispensed from a threat booster along with reentry vehicles might include objects and material that are designed to decoy or add noise to both radar and to infrared sensors. The size of the debris cloud is typically kept small to provide masking and to stress the ability of sensors to resolve and discriminate reentry bodies from other objects. The countermeasures attempt to defeat the traditional discriminants for radar by stressing the received radar signal to noise,

coherence, and bandwidth. Against infrared sensors, the stressed parameters are signal to noise, resolution, number of bands, and revisit time.

The ability to successfully discriminate the target warhead from other objects in its vicinity is critical to the success of NMD and is at this time an unproven technology in the context of integrated flight demonstrations.

The concept proposed for NMD in this paper includes the use of traditional infrared discriminants along with novel techniques that are enabled by the throw weight of the SLBM launcher that is used to boost the kinetic kill vehicles. Two ideas for discrimination include launching a high-acceleration precursor package into the vicinity of the threat cloud before the sequenced launch of kill vehicles. If the timeline does not permit this sequence, the precursor packages can be timed to arrive before the kill vehicles and a communication link would need to relay discrimination information to kill vehicles in flight.

The first idea for a precursor package is a gas-generating warhead that is optimized to generate the largest volume of non-condensable gases for a given mass. The "Sweep-up" discrimination idea would use the precursor warhead to impart an observable hydrodynamic impulse to the threat cloud. Observation of the trajectories of the objects in the threat cloud could then be used to discriminate between light and dense objects, the latter more likely to be the real warhead or very expensive decoys. Rough calculations indicate that a warhead with 100 kg of non-condensable gases delivered to within 100 meters of the warhead could impart an impulse of about $2500/\beta$ meters/sec, where β is the ballistic coefficient in kg/m2. This would be

sufficient to result in observable separation of the warhead from lightweight decoys and debris using the bus-mounted sensor.

Another idea for a precursor package is a dispenser of a planar cloud of small metallic pellets. A high-resolution optical sensor mounted on the bus would then be used to count the density of scintillation flashes as the pellets swept past the threat cloud at 10-12 km/sec closing velocity. The objects with greater mass would exhibit the largest optical response. The sensitivity of the optical sensor would need to be adjusted to avoid blooming during the pellet impact events.

Although neither of these discrimination techniques has been subjected to extensive analysis, they are illustrative of the design space that is afforded by the use of the SLBM launcher.

Kinematic Footprint

The dimensions of the kinematic footprint are a function of the following parameters:
- threat trajectory
- the interceptor booster
- the earliest fire control track that is provided by the tracking sensor
- fire control and battle management delays

It is also a function of system constraints such as:
- minimum intercept altitude
- minimum closing velocity for lethality
- approach angle constraints for seeker operation

Threat trajectories that are short-ranged or very depressed may delay the time when sensors can establish a track and will shorten the time that the interceptor has to fly out to reach the target before it hits a minimum intercept altitude.

For a fixed sensor-threat trajectory timeline, interceptor boosters that provide higher terminal velocities enhance the ability of kill vehicles to fly out to more distant intercept locations.

The kinematic reach for the proposed SLBM launcher is illustrated evaluated by simulation for a 9000 km range ballistic threat under the assumptions that SBIRS-low provides a fire-control track with a 300 sec time delay from threat booster launch, and with constraints of 300 km minimum intercept altitude and 5 km/sec minimum closing velocity. The simulation includes a massive search for the boundary of feasible fire control solutions that satisfy all constraints. The geometry of the search is illustrated in Figure 2 below.
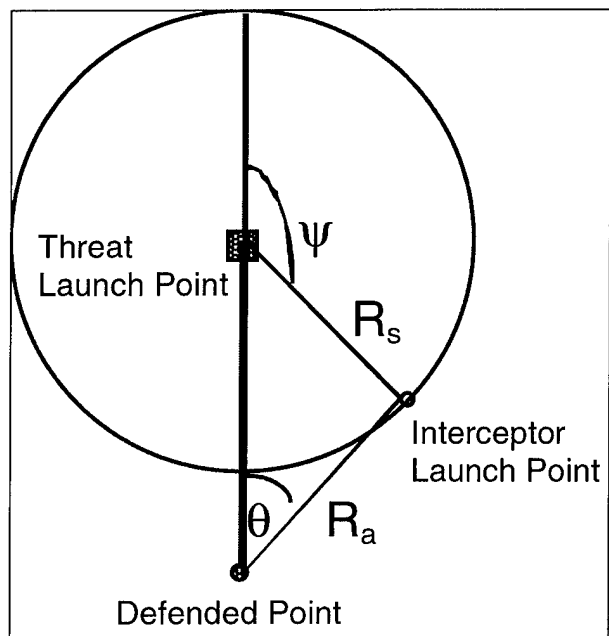

Figure 2. Geometry for intercept feasibility search.

The feasible region can be cast in the variables Rs and ψ, where Rs is the distance from the threat launch location to the interceptor launch location, or the variables Ra and θ, where Ra is the distance between the interceptor launch location and the defended point. The former is more useful

to depict the defended region from a specified interceptor launch location whereas the latter speaks to the operational area in which defenders must be emplaced to defend specified points. The results of the search for the proposed concept are given in Figures 3 and 4 below in the indicated coordinates. The part of the curve with cruciform symbols represents the assertion of the minimum intecept altitude constraint on the overall solution. The part of the curve plotted with the open circles represents the assertion of the minimum closing velocity constraint on the shape of the solution.
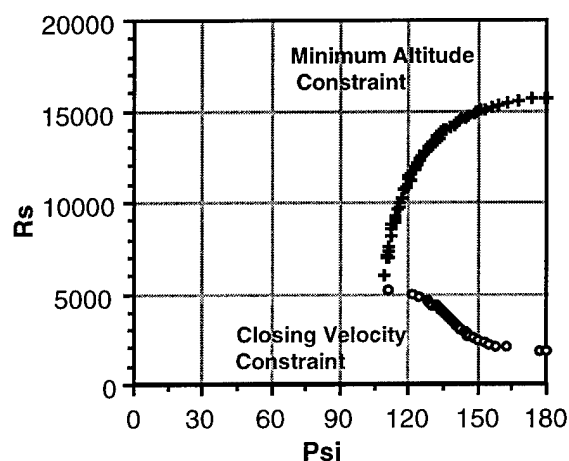
Figure 3 Feasible intercept solutions in defended area coordinates

The large values for the distance from the threat launch location in Figure 3 are in part due to the range of the ballistic threat. The angles with θ greater than 90 degrees in Figure 4 include intercept crossing angles that combine the velocities of both vehicles

and stay well clear of the closing velocity constraints. Small angles on this plot are what might be loosely termed "tail-chase shots" where the feasibility curve is limited by the closing velocity constraint.
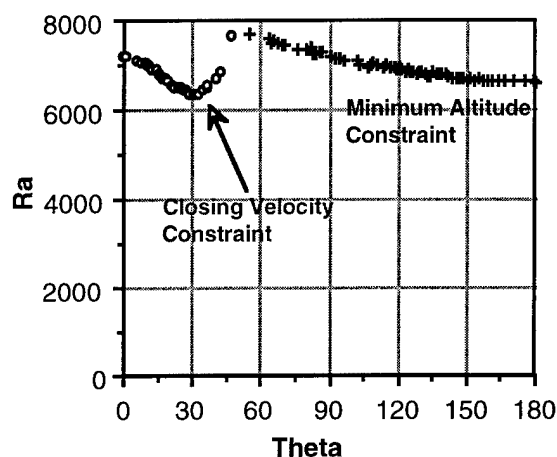

Figure 4 Feasible intercept solutions in operational area coordinates

To translate these data into geographic terms that are more readily assimilated, the data are transformed in Figures 5 and 6 to defended region footprints corresponding to two different intercept launch locations. The hatched area depicts the region of defended impact points. The NMD submarine is at the dot at the mid-Atlantic location in Figure 5 and provides protection to the hatched region against the 9000 km ballistic threat from any launch location.
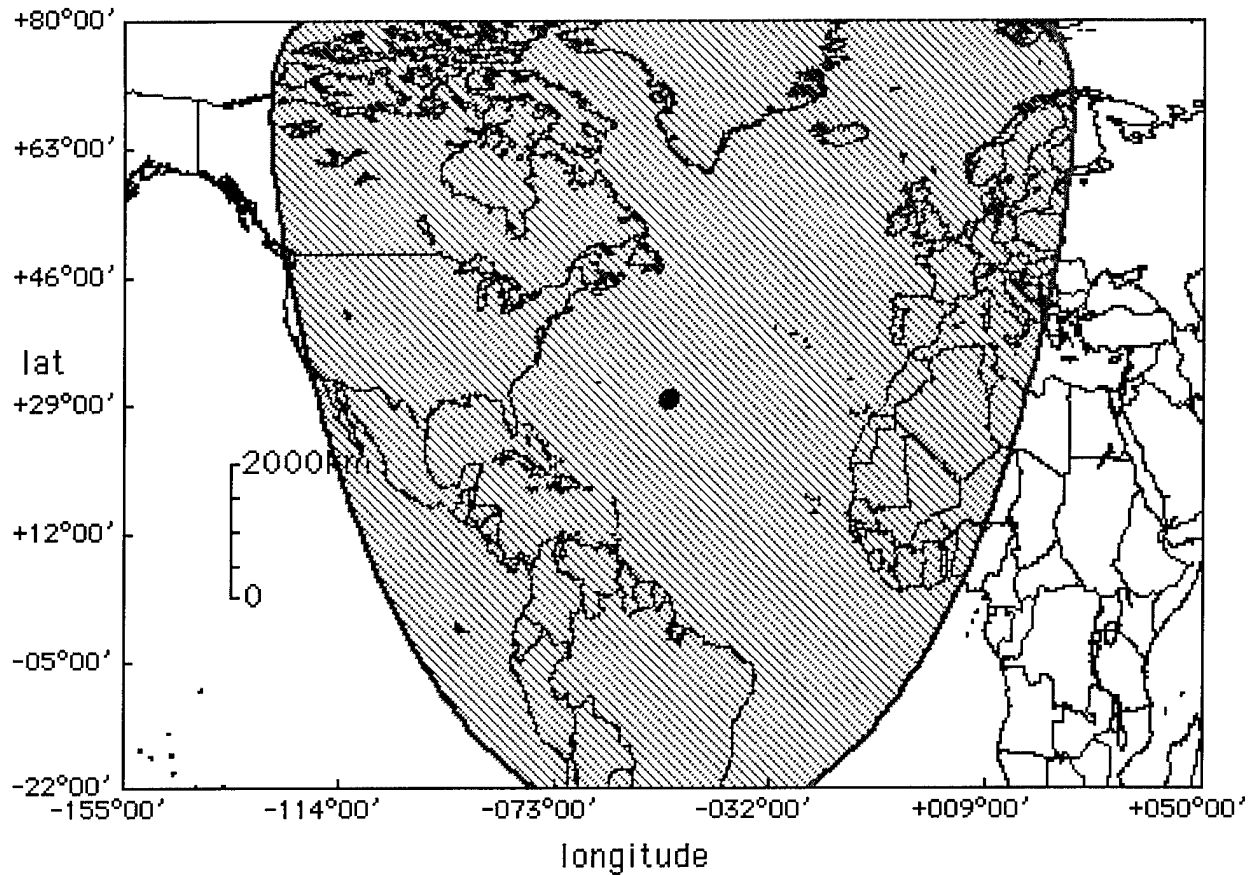
Figure 5 Global kinematic footprint from mid-Atlantic station

The size of the region is dramatic and derives from the combination of early track coverage from SBIRS-low and the large ballistic reach of the SLBM booster.

Figure 6 illustrates the coverage from a mid-Pacific station. Two submarines would appear to provide NMD for all 50 states as well as regional coverage for allies against the 9000 km ballistic threat.
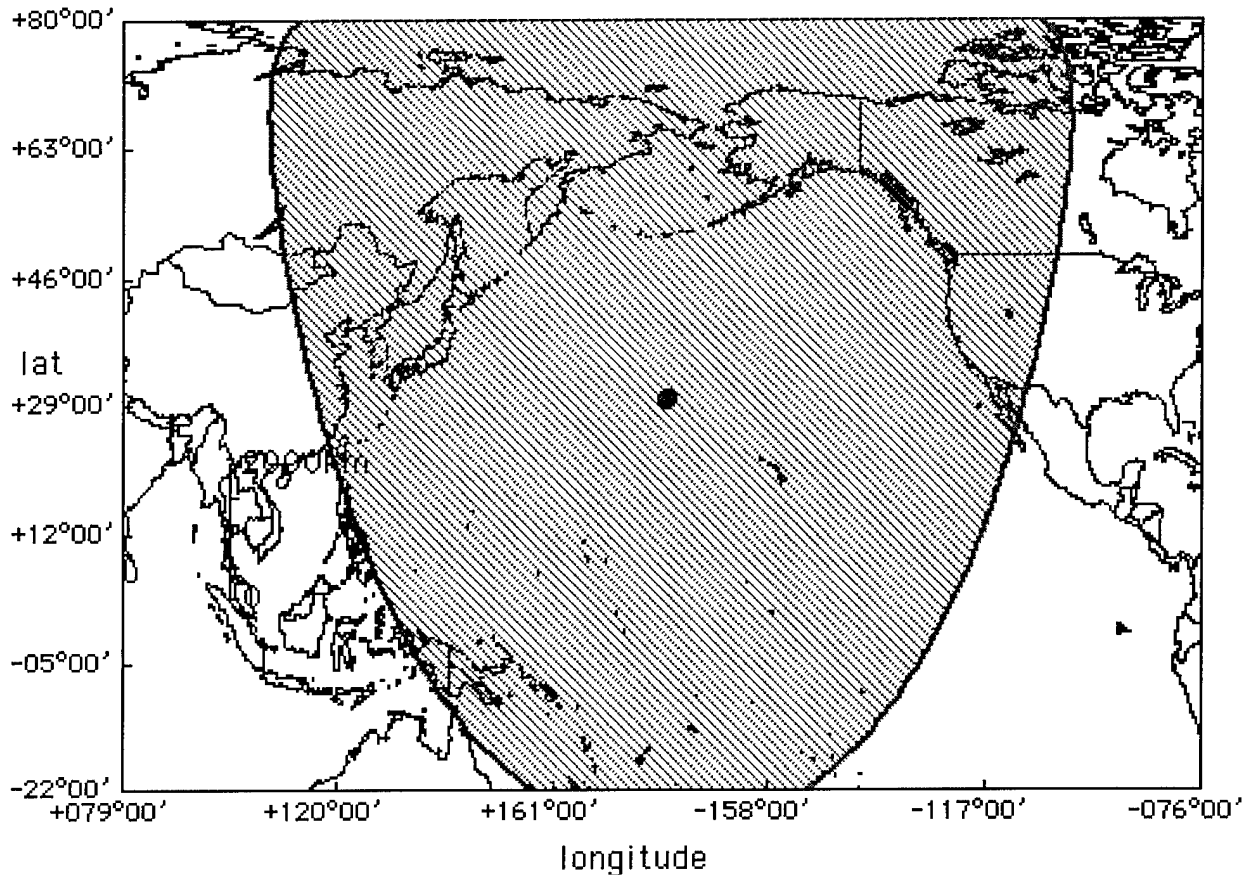
Figure 6 Global kinematic footprint from mid-Pacific station

Conclusion

The concept presented here represents some "out-of-the-box" thinking that was initiated and supported on Draper Laboratory internal funding and presented to the government in March 1999. Other individuals participating in the study included Paul Zarchan, John Elwell and Matt Ganz. The key features were the use of global information from SBIRS-low to provide fire control information and the use of an NMD interceptor that employed SLBM boosters to launch discrimination packages and multiple kinetic kill vehicles. That combination provides nearly global reach without the use of ground-based radar.

The simulation analysis included booster trajectories, sensor and composite tracking filter performance, and intercept trajectories leading to verification of kinematic timelines and satisfaction of intercept constraints. The concept supports the ability to employ novel techniques to address the contentious problem of discrimination, although this aspect of performance remains to be analyzed in detail. The overall potential of this concept would seem to warrant further exploration.

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June 12, 2000

Roger Medd
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Dear Roger:

Enclosed are two copies of my paper (#3-7) in Paul Zarchan's session (3) for the upcoming BMDO conference. The work was performed under company IR&D and uses only unclassified estimates of physical parameters that are representative of technologies for system elements. The distribution statement is included on the first page and the (unclassified) classification appears on every page.

Thank you for your patience,

Sincerely,

Owen L. Deutsch
Principal Member Technical Staff